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# Softening and instability of natural slopes in highly fissured plastic clay shales

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**Abstract.** Softening is often considered to be the main cause of first-time slides in OC clay, but so far the mechanics of softening has not been satisfactorily explained. Bearing on laboratory data and field observations about landslides in tectonized highly plastic clay shales of Italian Apennines, the paper describes a process of soil weakening that could explain some failures of natural slopes.

## 1 Introduction

Geotechnical literature reports numerous well documented cases of first-time slides in OC clay, whose operative shear strength is lower than the peak measured on representative undisturbed samples. The contrast between the virtually available soil resistance, and the resistance that is really mobilised at failure, is usually justified by mechanical processes of soil weakening occurring prior to slope failure. Two fundamental processes are generally invoked: i) strain softening (Bjerrum, 1967), that is caused by non uniform plastic shear strains leading beyond the peak, the average soil strength mobilised along a developing slip surface (progressive failure); ii) softening (Terzaghi, 1936), that is generally associated with volumetric strains induced by swelling, that cause a time-depending decrease in the available peak strength.

Softening, i.e. the decrease in peak strength prior to failure, is the topic of this paper, that reports some observations on first-time slides in highly fissured plastic clay shales and data gathered in both laboratory and in situ tests.

## 2 Current ideas about softening

Softening is often invoked to justify slides in overconsolidated clay, but a general consensus about the mechanics of

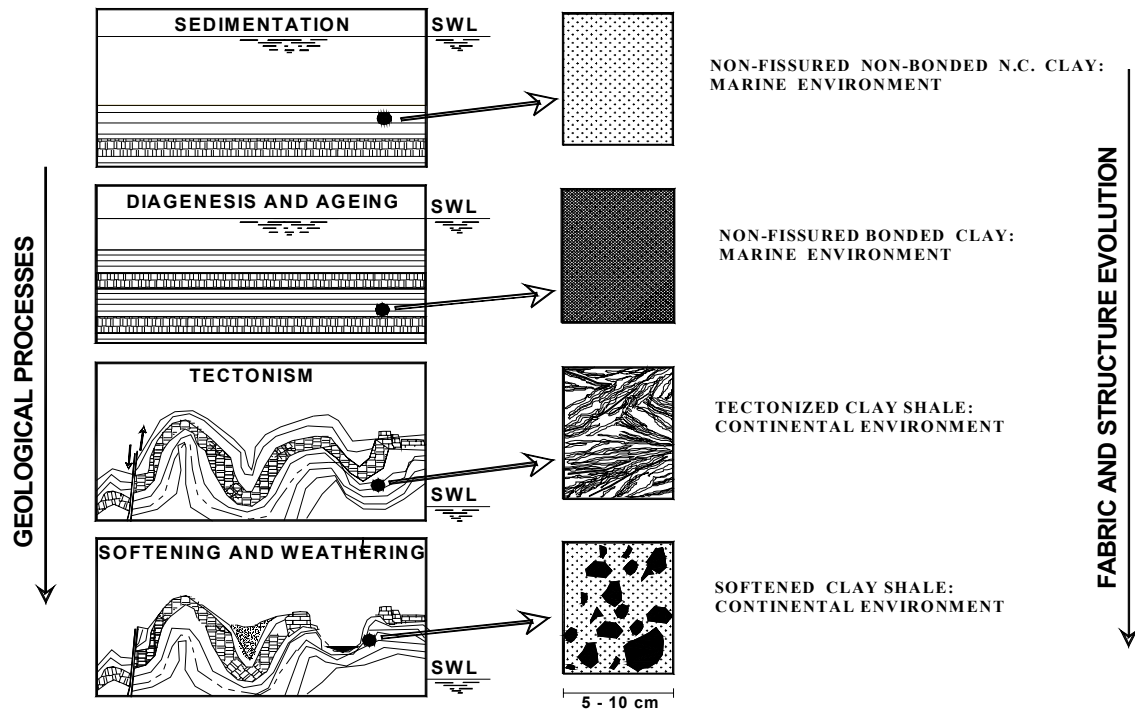
this phenomenon has not been achieved. Literally, softening is the result of water content increase due to a change of the state of stress.

Terzaghi (1936), first, observed that fissured OC clays can experience some shear strength decay as a consequence of swelling induced by unloading. Some English authors attributed to softening the delayed failure of cuttings in London Clay. In one of his latest paper on this subject, Skempton (1977) remarked that delayed failure is caused by dissipation of negative excess pore pressures triggered by excavation, a process that does not affect the shear strength parameters, but only the effective state of stress. However, he did not exclude that during the long-lasting phase of pore pressure equalization, some decay of the shear strength parameters can take place. In another important paper touching the same issue, Morgenstern (1985) outlined that swelling can provoke a decrease in the dilative and brittle behaviour of clay, causing a decrease in the shear strength through a loss of its component associated with overconsolidation: therefore, the long-term strength, the so called fully-softened strength, could be very close to the critical value.

According to Terzaghi (1936), the mechanism of shear strength decrease in fissured stiff clays is due to opening of fissures, swelling of the adjacent clay under practically zero confining stress and reconsolidation of clay under its own weight. However, this mechanism does not apply to all cases, especially to slightly fissured clay. Similar considerations as those made by Terzaghi, were reported by Skempton (1970) tens of years after, but thinking to fissures induced, also in intact clay, by mechanisms of shear.

Just to test, under the umbrella of the Critical Strength Theory, the effects of swelling on shear strength, Calabresi and Scarpelli (1985) and Rampello (1987) performed CIU triaxial tests on some Italian non-fissured or slightly fissured OC clays, pre-swelled in the laboratory under a very low confining stress. They noticed that swelling can bring about some decrease in cohesion due to increase in the water

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**Fig. 1.** Approximate representation of the geological history of the Apennines chain and associated fabric of clay shales (from Picarelli et al., 1998).

content. However, cohesion does not completely vanish and the soil behaviour remains dilative due to overconsolidation.

It is worth mentioning that softening, as described above, has some similarities with other phenomena that are responsible for time-depending decay of shear strength, such as weathering, slaking, i.e. soil destructureation caused by cycles of wetting-drying or of freezing-thawing (Botts, 1998; Graham and Au, 1985) and fatigue (Lacerda, 1989; Eigengbrod et al., 1992). Through accumulated plastic strains, all these phenomena, generally concentrated in the most superficial soil layers, can determine a loss of that part of the shear strength that depends on interparticle bonding, causing a reduction in cohesion. Therefore, they affect only bonded clays. Leroueil and Vaughan (1990) and Hight et al. (2002) assume that even simple swelling can provoke destructureation of bonded clays. This idea has been recently resumed by Takahashi et al. (2005) bearing on the results of laboratory tests on undisturbed specimens of London clay.

All mechanisms mentioned above show how complicated is the interpretation of slope instability in stiff overconsolidated clay and clay shale, since more than one of them can contemporaneously act in the same slope at same time. Furthermore, strain-softening (progressive failure) and rate effects can play an additional and significant role. However, laboratory data and field observations on highly fissured plastic clay shales of Italian Apennines show that a decrease in the shear strength could be caused by chemical-physical processes provoked by exposure of soil to fresh water.

### 3 Fabric and instability mechanisms in tectonized clay shales in the Apennines chain, Italy

Tectonized clay shales are widespread in the Apennines chain, Italy. The chain is the result of orogenesis, and is constituted by a thrust sheet sequence of superimposed nappes of clay and competent rock. Figure 1 shows a schematic representation of possible effects of the geological history of the chain on the structure of fine-grained deposits of marine origin.

Figure 2 shows a specimen of tectonized clay shale. It is highly fissured and sheared as a result of tectonism. Fissures are planar to curved, and polished to slickensided, thus their shear strength is certainly close to the residual value. Fissures are very small and closely spaced, intersecting each other: as a result, they subdivide the material into very small fragments (shear lenses, usually called “scales”) whose size is in the order of some millimetres to a few centimetres. However, superimposed persistent shear discontinuities are generally widespread in the soil mass.

As a result of this complex fabric, the mechanism of failure of tectonized clay shales is characterized by localization of deformation and slipping of soil along a system of nearby and mutually intersecting discontinuities (fissures and/or persistent shears), as in Fig. 3. Therefore, the available peak strength is quite low, because it depends on the friction angle along fissures, that is closely around residual, and on a sort of “angle of roughness”, that is a function of the profile of the

slip surface (Fig. 3), i.e. of continuity, spacing, orientation and shape of fissures.

For increasing confining stresses, the influence of this angle of roughness is smaller and smaller, and the resistance of clay can drop below the critical strength measured on reconstituted soil, tending towards the residual value (Picarelli et al., 2002).

Outcrops in tectonized clay shales are generally covered by a softer and destructured clay generated by weathering and swelling. A strong and fast increase in water content can be also caused by cutting. As a result of these phenomena, the system of fissures tends to disappear, and the clay shale progressively turns into an apparently non-fissured material. However results of laboratory tests on samples taken from softened covers suggest that fissures can be hidden, nevertheless affecting the shear strength.

Urciuoli (1990) reviewed the Italian literature on landslides in highly fissured tectonized clay shales, showing that flow-like movements are most widespread than other types of landslide.

This remark suggests that softening plays an important role on slope behaviour, since it normally favours the development of landslides of flow style. As a matter of fact, geomorphological field investigations indicate that slope failure can be followed by a fast increase of water content that goes on with a change of the movement style from slide to flow (Pellegrino et al., 2004).

#### 4 Land evolution and slope instability in the Bisaccia area, Southern Apennines

The Bisaccia hill is sited about 100 km North to Naples (Fig. 4). It is elongated in the South-North direction and is constituted by a slab of slightly cemented conglomerates resting on tectonized highly plastic clay shales of marine origin ( $CF=60\% \div 70\%$ ;  $WL=110\% \div 190\%$ ) that extensively outcrop in a wide area around the hill. The hill is the result of erosion started some hundreds thousands of years ago along two parallel faults. Erosion dismantled the upper conglomerates, leaving the hill in the middle (Fig. 5). Today, the bed of the two valleys is located within the fine-grained formation. The uppermost part of hillslopes, in conglomerates, is quite steep, whereas the lowermost part, in clay shales, is much gentler. Further hills rising in the same area display similar features.

As a consequence of continuous stress change associated with still active erosion, clay shales experience continuing deformation. In particular, the bed of the two valleys is rising because of swelling, while the hill is sinking and spreading laterally due to squeezing out of underlying clay shales. As a result, the conglomerate slab is highly fractured. This deformational process is accelerated by earthquakes, that have a return period ranging between thirty and fifty years. In particular, the strongest ones are responsible for post-seismic



Fig. 2. The highly fissured tectonized Bisaccia clay shale.

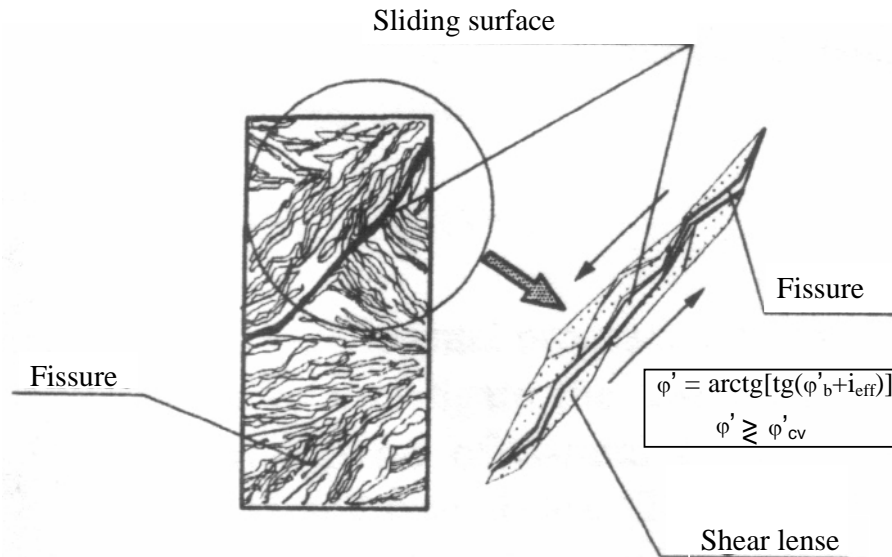
subsidence caused by dissipation of excess pore pressures induced by shaking (Di Nocera et al., 1995).

Geomorphological surveys and monitoring support the proposed model of land evolution. Deficient pore pressures, measured with vibrating wire piezometer installed in depth in the middle of the eastern valley, can be explained only by the effects of erosion, whose rate is faster than the rate of excess pore pressure dissipation. In contrast, monitoring of pore pressures in clay shales overlain by the hill, carried out after the strong Irpinia earthquake (1980), allowed to record positive excess pore pressures induced by seismic shaking. Numerical analyses bearing on extensive and careful laboratory investigations support these considerations (Di Nocera et al., 1995; Lampitiello et al., 2001).

The high erodibility of Bisaccia clay shales is directly recognizable in site by geomorphological investigations. In fact, running waters can rapidly excavate narrow and steep gullies: in a few years, these can attain depths of metres.

Steep slopes in clay shale are subjected to either deep slides or shallow mudslides. A couple of examples are shown in Fig. 6. The first photograph (Fig. 6a) shows quite a deep slide along a flank of the Bisaccia hill: the slide develops in grey clay shales, involving a brown conglomerate block. The second photograph (Fig. 6b) shows a shallow mudslide in grey clay shales.



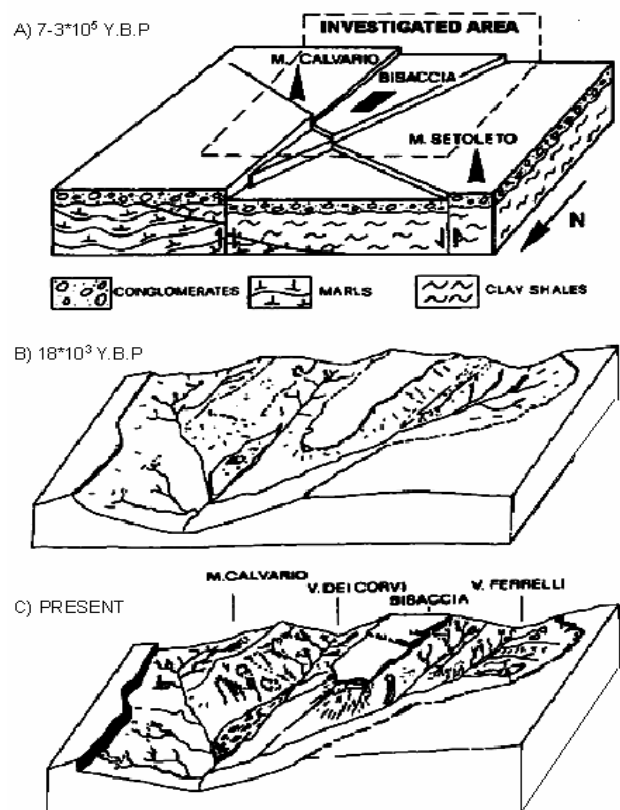


**Fig. 3.** Typical mechanism of failure of tectonized clay shales in triaxial tests and factors governing the friction angle,  $\phi'$  (from Olivares and Picarelli, 1999):  $\phi'_b$  is the “basic” friction angle along a perfectly planar and polished surface,  $i_{\text{eff}}$  is the “angle of roughness” and  $\phi'_{\text{cs}}$  is the friction angle at critical state.



**Fig. 4.** The Bisaccia hill.

Accounting for the very low shear strength of soil in saturated conditions ( $\phi' = 15 \div 25^\circ$ , depending on effective normal stress), steep slopes in clay shale, that can locally reach angles of  $40^\circ$  and more, can remain stable for long time only thanks to suction (Olivares, 1997). Swelling pressures measured in the laboratory on superficial samples directly taken from outcrops, prove the existence of a high suction. In fact, values as high as 0.6 to 1 MPa have been measured in oedometer and isotropic compression tests that have been performed, as usual, in a bath of distilled water. Such high suctions are due to the effects of erosion (Picarelli and Urciuoli, 1993), combined with the steepness of slopes and the low conductivity of clay, that govern hydraulic boundary conditions and capillary forces. In particular, in saturated



**Fig. 5.** Geological history of the Bisaccia hill according to Di Nocera et al. (1995).



**Fig. 6.** Landslides in clay shale along steep slopes: (a) a deep slide affecting the hillslope; (b) a mudslide.

conditions the soil permeability is as low as a  $10\div 13$  m/s. Prolonged rainfalls cause a decrease in suction and in the associated cohesion, leading to slope instability. The depth reached by the advancing wet front due to water infiltration depends on the duration of the event, on the slope of the ground surface and on soil permeability. Generally, landslides have a very small thickness. As shown by Pellegrino et al. (2004), formation of mudslides, as in Fig. 6b, can be



**Fig. 7.** Landslides occurring on gentle slopes.

due to the rapidity of debris deposition at the toe of the slope, that cause a building up of excess pore pressure in the fine-grained debris, under its own weight.

Also deep slides occurring along the steep flanks of the hill, as in Fig. 6a, are triggered by suction decrease. Possibly, the mechanism of failure is progressive, starting from the toe of the slope, where suction decreases faster than in depth.

Figure 7 shows some shallow landslides (either slides or flows) on a gentle slope. In these geomorphological conditions the water table is very close to the ground surface for a great part of the year; hence, suction does not seem to play an important role. Therefore, if the morphology of slope does not change with time, the minimum safety factor, attained in wet seasons, should remain more or less the same. In this case, instability seems to be a consequence of a time-depending process of shear strength decrease, here called softening, more than of pore pressure changes.

## 5 Likely effects of infiltration on the shear strength of Bisaccia clay shale

As shown above, the mechanism of failure and the shear strength of tectonized clay shales are strongly affected by fabric. In its “overconsolidation” range, the soil is dilative and slightly brittle. This is shown in Fig. 8a where are reported the results of conventional direct shear tests on the marine Bisaccia clay shale, run, as usual, in a bath of distilled water, under a normal stress less than the overconsolidation pressure. Figure 8b shows the results of further tests performed after a stage of swelling in the same shear box under a normal stress of 10 kPa, and a successive stage of consolidation under the established normal stress, that falls in the same range of values as in the previous case. A comparison between the two figures shows that pre-swelling determines a radical change of soil behaviour, that becomes contractive and ductile, leading to a significant shear strength decrease: since in both cases the failure envelope is slightly

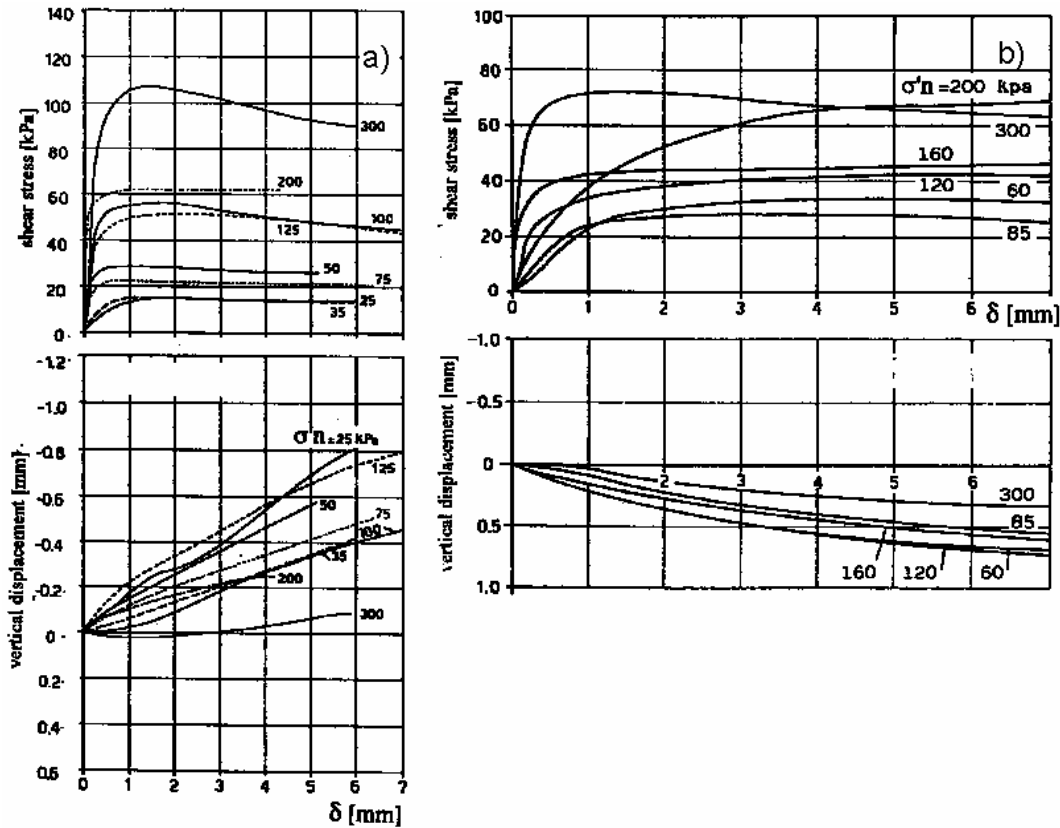


Fig. 8. Results of direct shear tests on the Bisaccia clay shale (from Cicoella and Picarelli, 1990): (a) conventional; (b) after a stage of swelling under a normal stress of 10 kPa.

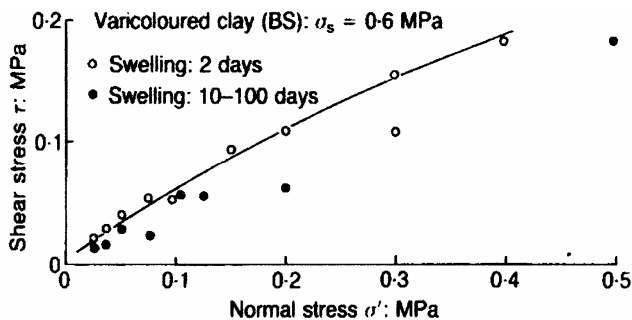


Fig. 9. Results of direct shear tests on the Bisaccia clay shale for normal stresses lower than the swelling pressure (from Picarelli, 1991).

non-linear, the linear fitting of data furnishes some cohesion, that is 11 kPa in the first case and 16 kPa in the second one, but the friction angle after pre-swelling drops from  $26^\circ$  to only  $11^\circ$  (Cicoella and Picarelli, 1990). Such a low value of the friction angle deserves some further comment.

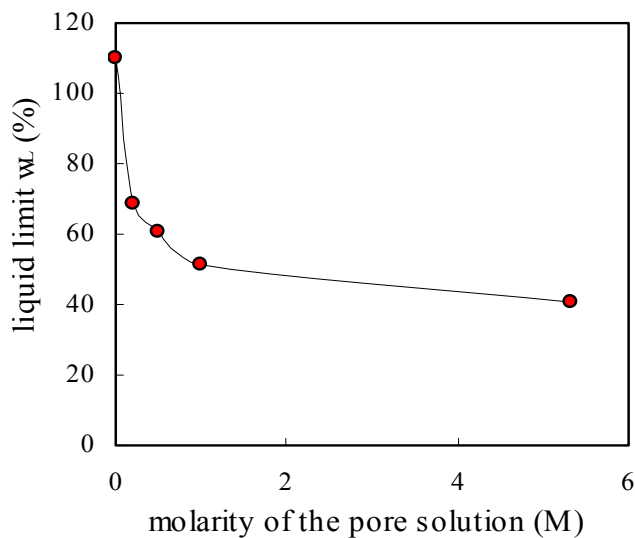
Figure 9 shows the results of further tests conducted under normal stresses lower than the swelling pressure (around 0.6 MPa). While a part of the specimens were allowed to

swell, as usual, for 48 h, others were sheared only after 10 to 100 days of swelling, during which they experienced high volumetric strains. The difference in shear strength is very clear. Once again, the parameters of shear strength are dramatically affected by the magnitude of swelling: in fact, the cohesion measured after a long stage of swelling falls from 11 to 9 kPa and the friction angle from  $26^\circ$  to  $18^\circ$ .

All these results show that swelling in distilled water (either primary or secondary) is responsible for a change of soil behaviour and shear strength. Starting from works carried out by Di Maio (1996a, b), Picarelli et al. (1998) assume that the peak strength decrease experienced by marine Bisaccia clay shale is caused by physical-chemical processes due to exposure to and absorption of distilled water, and consequent change of interparticle forces.

An impressive idea about the susceptibility of marine Bisaccia clay shale to any change of pore liquid is shown in Fig. 10, that shows the dependence of the liquidity limit on the molarity of a NaCl solution. Such a solution is probably more similar than distilled water to the natural pore liquid, in turn depending on the natural deep marine sedimentation environment. As shown, the liquidity limit obtained with distilled water is about two times the one obtained with NaCl solution, regardless its molarity.



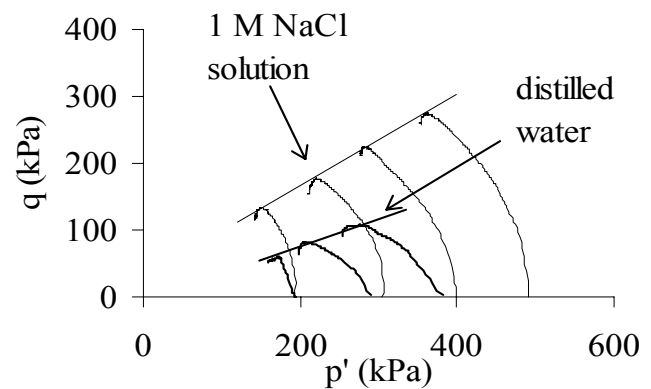


**Fig. 10.** Dependence of the liquidity limit of the Bisaccia clay shale on the nature of pore liquid (from Picarelli et al., 1998).

Figure 11 reports the results of triaxial tests executed by Di Maio and Onorati (2000) on reconstituted normally consolidated specimens obtained by mixing powdered clay with distilled water and with a 1 M NaCl solution. It shows that the friction angle at constant volume depends on the nature of pore liquid. Similar results have been obtained for the residual friction angle, that is  $8.6^\circ$  in a NaCl solution and only  $4^\circ$  in distilled water (Di Maio, 1966b).

These data suggest that any variation of the natural environment can cause a change of the field soil behaviour. An example of the possible effects of infiltration of fresh water in a natural deposit subjected to swelling is shown in Fig. 12, that reports the results of oedometer tests carried out on two couples of undisturbed specimens of marine Bisaccia clay shale taken in the middle of the western valley, respectively at a depth of 2.5 and 21 m. A specimen of each couple was tested in a bath of distilled water; the other one was tested in 1 M NaCl solution. The influence of the nature of the bath on soil behaviour does not appear significant in the stage of compression, when the pore water is expelled from the specimen, but becomes prominent in the following stage of swelling, when some liquid is absorbed from the bath: in fact, the specimens tested in distilled water (and especially the one taken at the greatest depth) display higher strains than those tested in the solution. At the end of the tests performed in the NaCl solution, when the axial stress was 10 kPa, the solution was substituted with distilled water, giving immediately rise to further strong soil swelling.

These observations can justify the results of direct shear tests presented at the beginning of this section: primary and secondary swelling in distilled water provokes a chemical exchange between the distilled water and the natural pore liquid, an increase of the void ratio and a change of interparticle forces. As a consequence, also intrinsic soil properties,



**Fig. 11.** Comparison of the failure envelopes of reconstituted Bisaccia clay mixed with distilled water and with a NaCl solution (from Di Maio and Onorati, 2000).

as the indexes of compressibility and swelling or the critical and residual friction angle of reconstituted soil, change. In addition, also the general soil behaviour, that turns from dilative into contractive, seems to change (Fig. 8). Both effects contribute to a decrease in the shear strength.

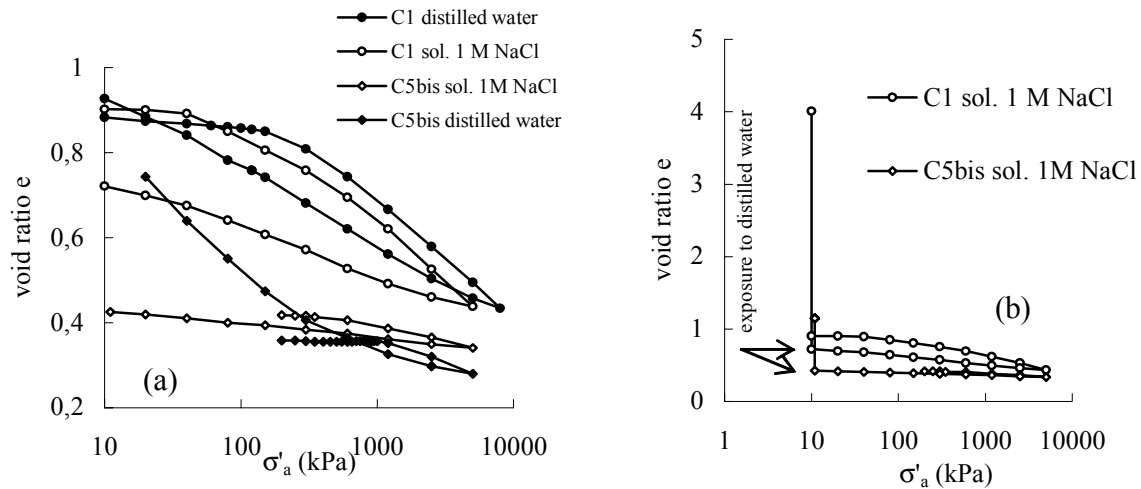
According to these results, the high swelling index exhibited in oedometer tests by several American highly plastic clay shales and attributed to passive failure occurring during unloading (Singh et al., 1973) or to soil destructuration (Leroueil and Vaughan, 1990), could be simply an effect of osmotic swelling, as in Fig. 12a, giving rise to a progressive change of the composition of pore liquid.

Bearing on these results, it comes naturally to assume that shallow layers of marine OC clay subjected to swelling induced by erosion, may experience a time-depending shear strength decrease, usually called softening, due to infiltration of fresh rain water. This process is facilitated by opening of fissures, and leads to long-term slope failures.

It is worth mentioning that literature reports some cases in which similar physical-chemical phenomena seem to play a prominent role on slope behaviour (see for instance Hawkins, 1996). An interesting case of mudslide movement seemingly governed by changes of the chemistry of pore liquid has been described by Moore and Brunsden (1996). The authors find that the threshold of pore pressure required to reactivate the mudslide in wet seasons is lower than that required to stop movement. They associate this apparent inconsistency with changes of pore water chemistry occurring during dry periods.

To further investigate the properties of Bisaccia clay shale, a campaign of in situ tests was carried out in the eastern valley. The upper part of this is occupied by a slow active mudslide whose thickness ranges between 3 and 6 m. In this area 18 CPTU tests and 6 environmental cone tests were performed; these last allowed to measure the pH of pore water. The tests were carried out through the mudslide body until the underlying parent stable formation.





**Fig. 12.** Results of oedometer tests on undisturbed specimens exposed to different liquids (from Picarelli et al., 1998).

Figure 13 shows some results of the tests performed in the experimental field. In both cases, the tip resistance in the mudslide body is extremely small and does not show any clear trend with depth, locally revealing more resistant zones probably due to the presence of rock fragments or of lithorelicts of the parent formation embedded in the debris. However, since the cone penetrates into the cover of the stable parent formation overlain by the mudslide body, the measured strength starts to increase with depth. According to well known relationships between tip resistance and undrained cohesion, the minimum value of this last in the mudslide body can be assessed in the range between 10 and 20 kPa, while in the cover of the stable parent formation it reaches values of hundreds of kPa. The measurements made with the environmental cone show that the mudslide body is quite acid, having a pH less than 7, with minimum values of 4–5. However, differently from the tip resistance, the pH gradually increases with depth even in the mudslide body. In strong contrast with the features of the uppermost remoulded soils, the pH measured in the parent formation is always higher than 7.

The entire set of data gathered in the site investigation seem to confirm previous considerations about the effects of swelling on the mechanical behaviour of Bisaccia clay shale. In fact, infiltration of rain water, that can reach quite a great depth because of opening of cracks during movement, permanently exposes the mudslide body to fresh water. Induced osmotic phenomena lead to a progressive variation of inter-particle forces and of mechanical soil properties. The lower pH of these soils, that is also affected by decomposition of organic matter, could be an indicator of such a process.

Infiltration of rain water below the mudslide body is less easy because of the lower soil permeability, of the decreasing density of opened cracks, and of the decreasing aperture of these last. This might explain the abrupt change of pH at the interface with the lower formation.

Such physical processes are likely to develop also in those fine-grained deposits that cover stable gentle slopes, causing a slow time-depending shear strength decrease, usually called softening, and consequent long-term slope failures. Since these processes are also responsible for large increase of soil porosity, the development of flow-like landslides seems more likely than that of slides, because of the softer soil response that leads to large deformations of the landslide body and, mostly, to high positive excess pore pressures, if undrained conditions establish (Pellegrino et al., 2004).

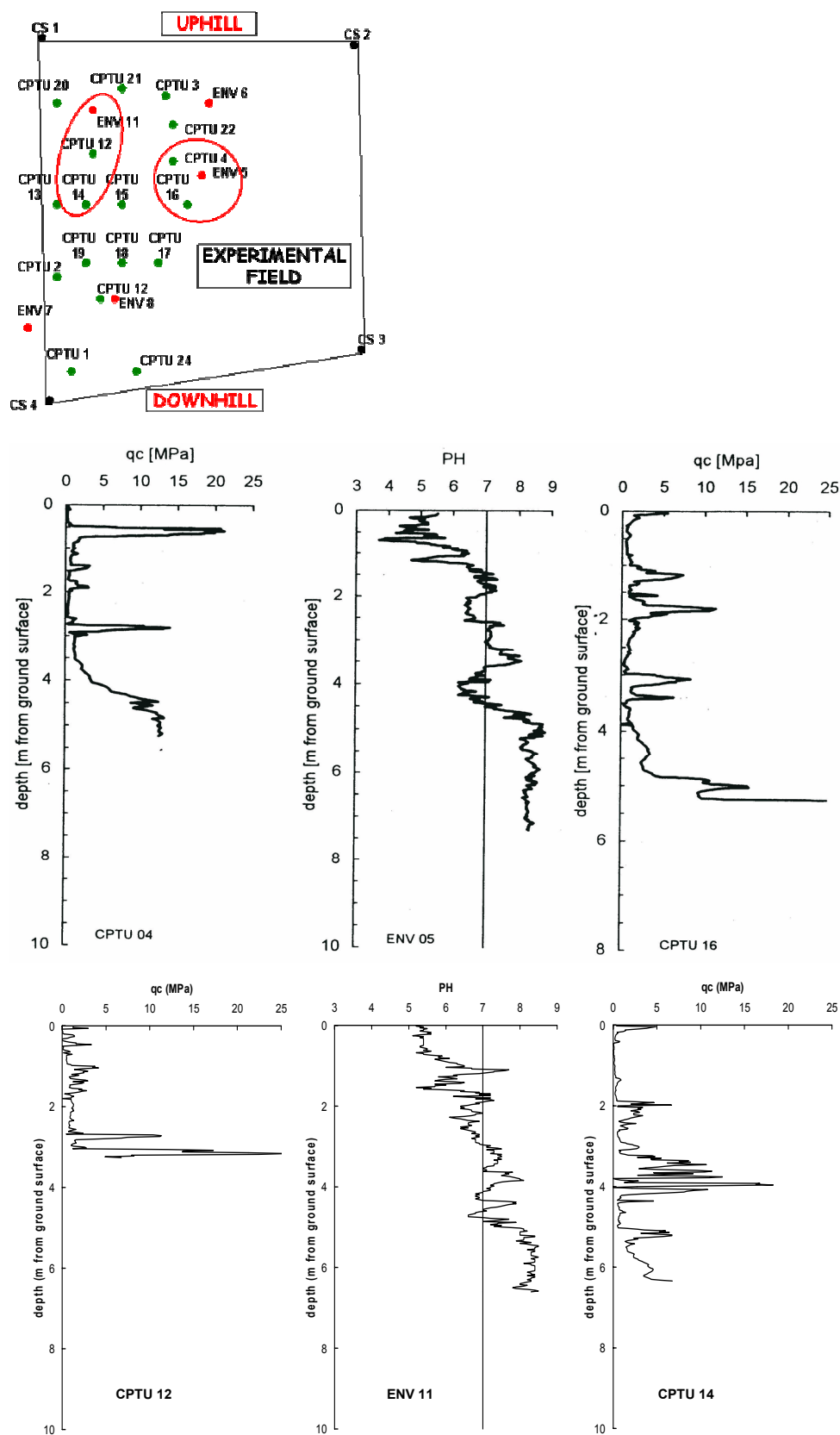
Naturally, described phenomena are more likely in highly plastic clay shales of marine origin, whose susceptibility to exposure to fresh water is much higher than in other formations.

## 6 Summary and conclusions

Geotechnical literature shows that the operative strength in first-time slides in OC clay is often less than the peak bulk strength measured in the laboratory. In the last seventy years, this fundamental observation intrigued very much researchers. The answer given so far to this question is not always satisfactory, probably because different mechanisms, often contemporaneously acting, can determine the same result. According to one of the most favourite explanations, swelling due to stress decrease can determine a reduction of the peak shear strength. Despite experience supports this observation, the mechanics of this phenomenon is not completely clear.

The paper shortly describes the features of landslides affecting natural slopes in tectonized highly fissured plastic clay shales of marine origin outcropping in a small area of Southern Italy. In particular, it has been observed that:

- slope failures affect either steep slopes or gentle slopes, displaying slide-like or flow-like movement patterns;



**Fig. 13.** Results of CPTU and environmental cone tests performed in the Bisaccia clay shale.

- they are triggered by time-depending processes of shear strength decrease;
- two different mechanisms of soil weakening, both caused by rainfall, seem to prevail: suction decrease and reduction of the effective shear strength parameters;
- first mechanism, that is responsible for instability of steep slopes, is due to a decrease in the cohesion associated with suction;
- second mechanism, that typically triggers instability of gentle slopes, is due to osmotic phenomena caused by exposure of clay shale to fresh water, and can govern the development of flow-like movements;
- similar phenomena of shear strength decrease due to exposure to fresh water seem likely in other formations of highly plastic overconsolidated clays of marine origin.

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